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Research and Development Report

An Infrared Study Using a Scaled Model

by

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Carderock Division, Naval Surface Warfare Center

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The infrared laws of similitude are applied to the problem of measuring the infrared contrast of a system by a laboratory study of scale models. Plans are detailed for an experiment and measurements to be made on a particular scale model. The role of dimensionless variables in the overall design of the experiment is emphasized. A complete list of typical measurements required is given, together with the measurement equipment to be employed. A discussion is presented of the manner in which measurement results are to be organized and graphically displayed.

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CONTENTS

FIGURES

TABLES

NOMENCLATURE

FLIR	Forward Looking Infra Red radiometer
H	heat power per unit volume
$\overline{H}$	dimensionless heat power
h	heat transfer coefficient
$\overline{h}$	dimensionless heat transfer coefficient
h_c	convective heat transfer coefficient
h_r	radiative heat transfer coefficient
I	light intensity
i	electric current
k	thermal conductivity
k_f	thermal conductivity of fluid
L	typical length
L_f	typical length convecting into a fluid
Pr	Prandtl number
T	temperature
$\overline{T}$	dimensionless temperature
T_a	air temperature
T_o	initial temperature at every position
T_w	water temperature
T_∞	a reference temperature, often chosen equal to the air temperature

NOMENCLATURE (Continued)

t	time
$\bar{t}$	dimensionless time
x	position
$\bar{x}$	dimensionless position
α	thermal diffusivity
μ	viscosity
ϵ	emissivity
π	any dimensionless variable, as in Buckingham's π theorem
ρ_f	density of fluid
σ	either the standard deviation or the Stefan constant in the T^4 radiation law
θ	direction angle of air or water velocity vectors with respect to laboratory frame of reference
$\vec{v}_a$	air velocity vector
$\vec{v}_w$	water velocity vector
∇	gradient operator

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ABSTRACT

The infrared laws of similitude are applied to the problem of measuring the infrared contrast of a system by a laboratory study of scale models. Detailed plans are produced for an experiment and measurements to be made on a particular scale model. The role of dimensionless variables in the overall design of the experiment is emphasized. A complete list of typical measurements required is given, together with the measurement equipment to be employed. A discussion is presented of the manner in which measurement results are to be organized and graphically displayed.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The focus of this effort is the applicability of the laws of similitude to the infrared (IR). For an existing scale model, in particular, the concern is in planning for measurements to be performed in a laboratory environment; see Fig. 1. The objective is to demonstrate how a typical IR experiment should be implemented for a given scale model. The procedures for such a typical laboratory IR experiment are provided in this report along with issues that underlie the application of scaling theory to the field of IR. In this regard the importance of casting the study within the framework of dimensionless variables between model and full-scale system is emphasized. The hope is that similarity lends validity to laboratory scale studies.*

Subsequently, an overview of a scaled IR experiment is given, with the description of a particular scaled model based on a full-scale PG-100 shown in Fig. 2. Construction details of the model, which will be of value over the course of IR experiments, are also provided. Details are presented for carrying out an IR scaled experiment. All relevant measurements to be made are listed.

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* "Laws of Infrared Similitude," P.O. Cervenka and L. Massa, NSWCCD Report CARDIVNSWC-TR-94/002 (Jan 1994).
"Analysis of Infrared Scaling Laws," L. Massa and P.O. Cervenka, NSWCCD Report CARDIVNSWC-TR-94/004 (Mar 1994).
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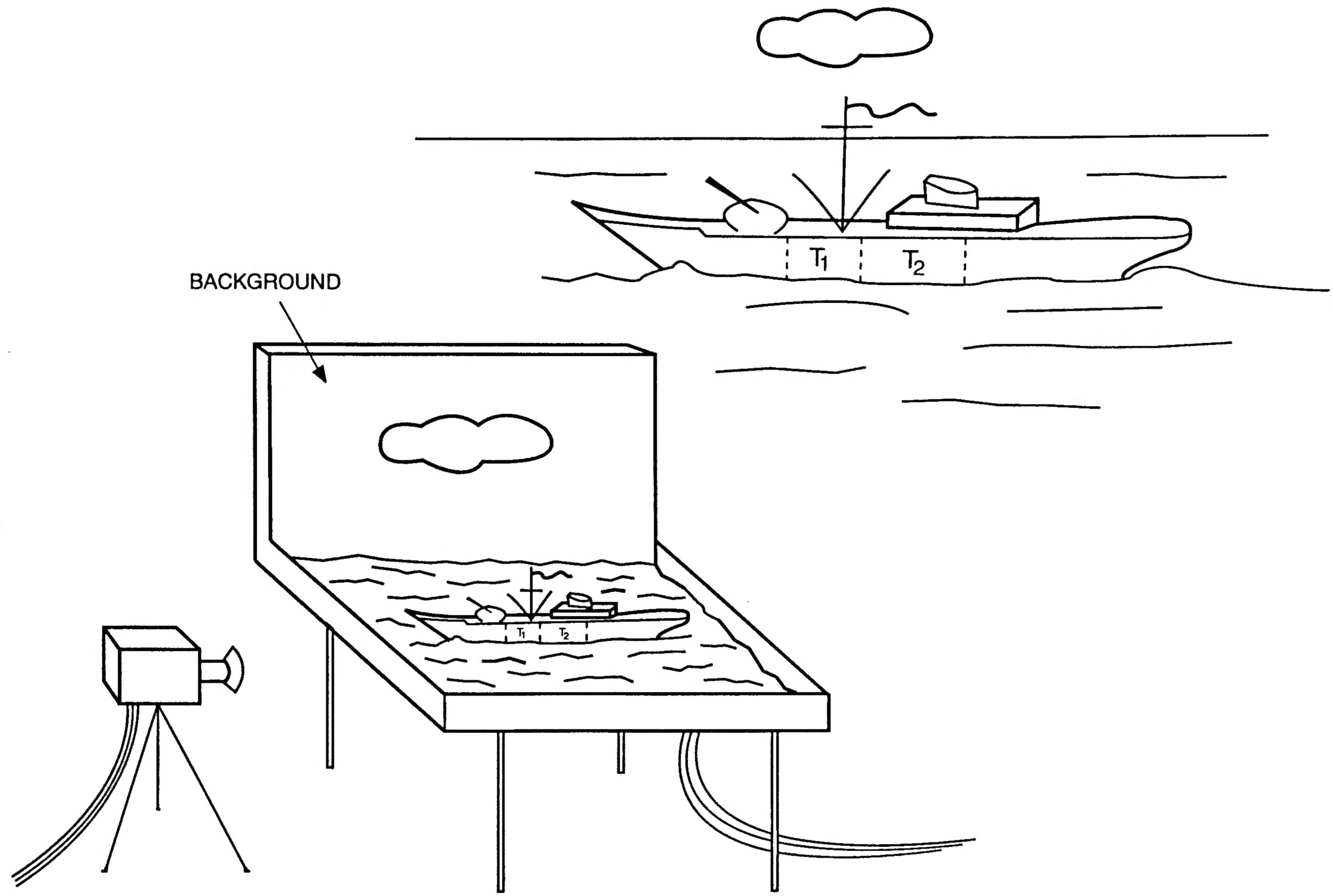

Fig. 1. Laboratory simulation of full-scale IR signature.

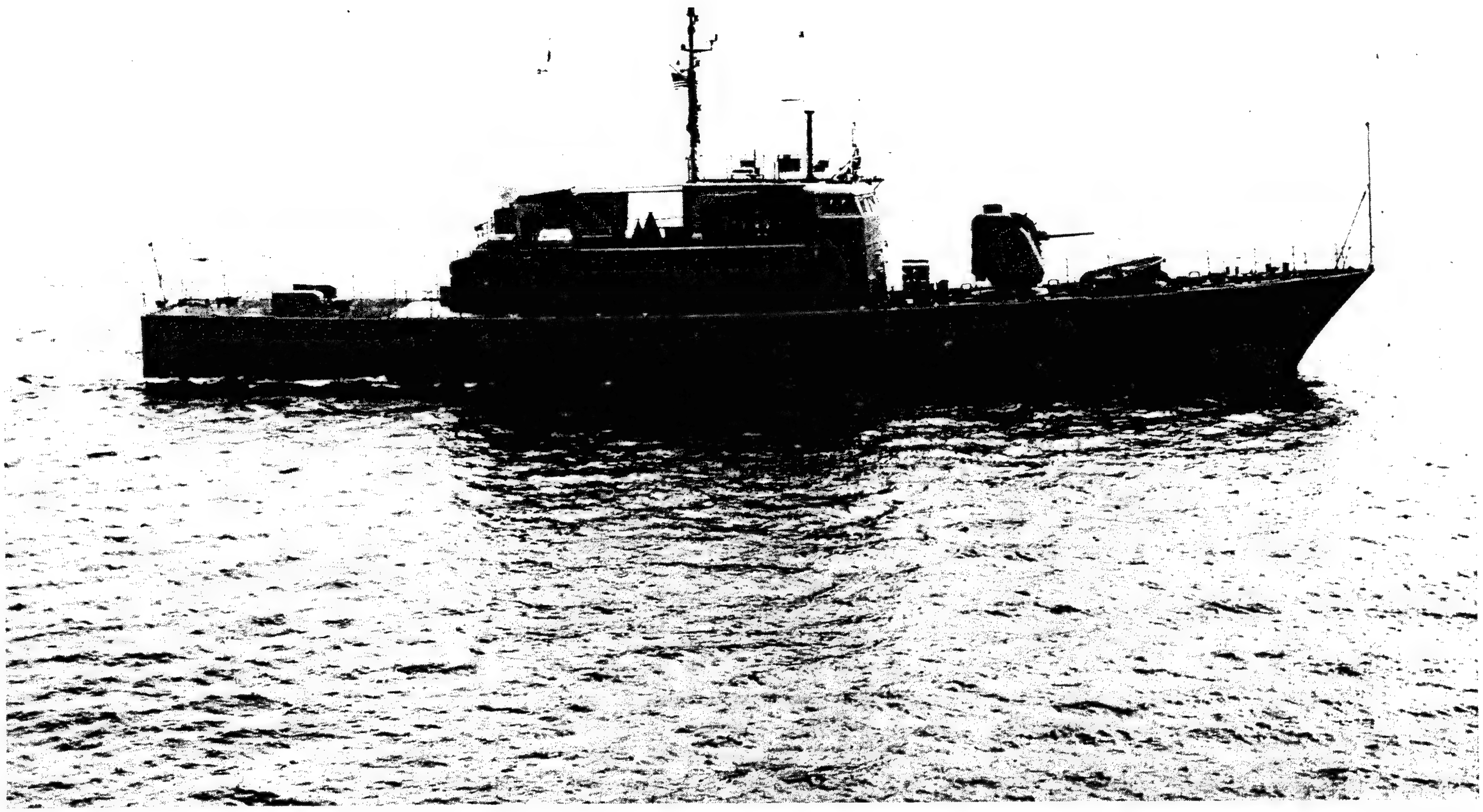

Fig. 2. PG-100 class patrol gunboat at sea.

Relevant dimensionless variables are listed together with their definitions in terms of measurable quantities. Variables required to be measured in a typical experimental run are listed, as well as the expected range of values to be studied. The types of instruments to be used for the measurement of the various variables are also indicated. The experiments are also defined by the thermodynamic parameters that characterize the materials of the scale model and its surroundings; a list of these parameters is presented. The validity of conclusions to be drawn from the scaled IR experiments requires that all of the various measurements be made using calibrated equipment. Thus, known systematic errors in the measurements will have been eliminated, and a measure of the random variance associated with equipment readings will be known. It is also valuable to know the uncertainty in the thermal parameters that characterize the materials of the experiment. In this way the usual rules of error propagation can be used to show that the experimentally obtained errors in the results fall within the range expected.

ESSENTIAL IDEAS OF IR SCALING THEORY

The geometrical similarity between model and full-scale system is necessary, but not sufficient to ensure thermal scaling. Since the temperature function is the source of the IR signal, in accordance with the Planck blackbody radiation law, the temperature behavior of model and full-scale system must also match. Thus thermodynamic similarity of model and full-scale system is also required for full IR similarity. Thermodynamic similarity is imposed when the heat equation is applied and expected to hold both for the scale model and the full-scale system. A comparison of analogous terms yields the IR scaling laws. The information inherent in the scaling laws may be reformulated by transformation to a set of dimensionless variables, also called π variables in the context of Buckingham's π theorem, leading to the statement: *Dimensionless temperature functions of scale model and full-scale system match only on condition that the dimensionless variables (from the heat equation) also match.*

The number of π's to be so matched is very small, consisting of $\overline{x}$, $\overline{t}$, $\overline{H}$, and $\overline{h}$, which are the dimensionless quantities related respectively to position, time, heat sources/sinks, and heat transfer coefficients (including both convective and radiative effects). The exact definition of each of the relevant π variables is tabulated and presented in the table of dimensionless variables. The general relation

$$\overline{T} = \overline{T}(\overline{x}, \overline{t}, \overline{H}, \overline{h}) \tag{1}$$

applies to either scale model or full-scale system. Hence, when independent variable π's are set equal between model and full-scale system, the result is equal dimensionless temperatures, $\overline{T}$, and therefore similar IR radiation from the hull. These results are applied later to the design of the list of physical measurements appropriate for IR scale studies and their analysis.

OVERVIEW OF SCALED IR EXPERIMENT

Infrared experiments that use IR scaled models under laboratory conditions are illustrated in Fig. 1. A full-size system is also shown where the hull reaches a temperature determined by the internal and external heat loads and the interaction of a system with its environment. The hull is segmented into isothermal pieces of temperatures T_1, T_2, etc. A one-to-one correspondence can be made between the isothermal pieces of the scaled model and the full-scale system it represents. This, of course, is the result expected on condition that the laboratory arrangement of dimensionless variables, i.e., π-variables, are set equal between full-scale system and scaled model. The purpose of scale modeling is to set the π's of the scale model equal to those of the full-scale system so that the temperature function of the hull and the IR radiation flowing from it may be studied within a laboratory environment with its associated advantages of low cost, convenience, and experimental accuracy.

DESCRIPTION OF SCALED MODEL

Consider an IR scaled model such as depicted in Fig. 3. Because it is necessary to sample the temperature at a variety of points, the scale model is constructed of separate modules based on the details of the full-scale gunboat shown in Fig. 4, which allows convenient placement of thermocouples as well as electrical and mechanical adjustments as the measurements program proceeds. Figure 5 shows the positions of the thermocouples that have been attached to the surface of the scale model. These thermocouples measure the temperature function of the hull. This will be useful in determining experimentally the convection heat transfer coefficient, h_c, of the hull. Figure 6 shows a three-chamber cooler used to control the temperature of three independent air streams pumped through tygon tubing into compartments of the scale model. The air temperatures are regulated by thermoelectric modules (TEMs), which are based on the Peltier effect, and the air temperatures are monitored by thermocouples in each of the three independent chambers. The flow of forced air through the scale model may be used to help "initialize" the interior surface temperatures, and to simulate the convective effects of the air conditioning system in the full-scale ship. The labels on the various equipment shown in Fig. 3 correspond to:

(a) a thermocouple read-out module;
(b) a power supply;
(c) tygon tubing to conduct the flow of forced air;
(d) a three-chamber air temperature regulator;
(e) an air pump;
(f) a scale model;
(g) color coded wires connected to all the thermocouples
(h) hollow stainless steel tubing that anchors the scale model in a rigid position and serves as entrance and exit for all electrical wires and tubes used in the scale model.

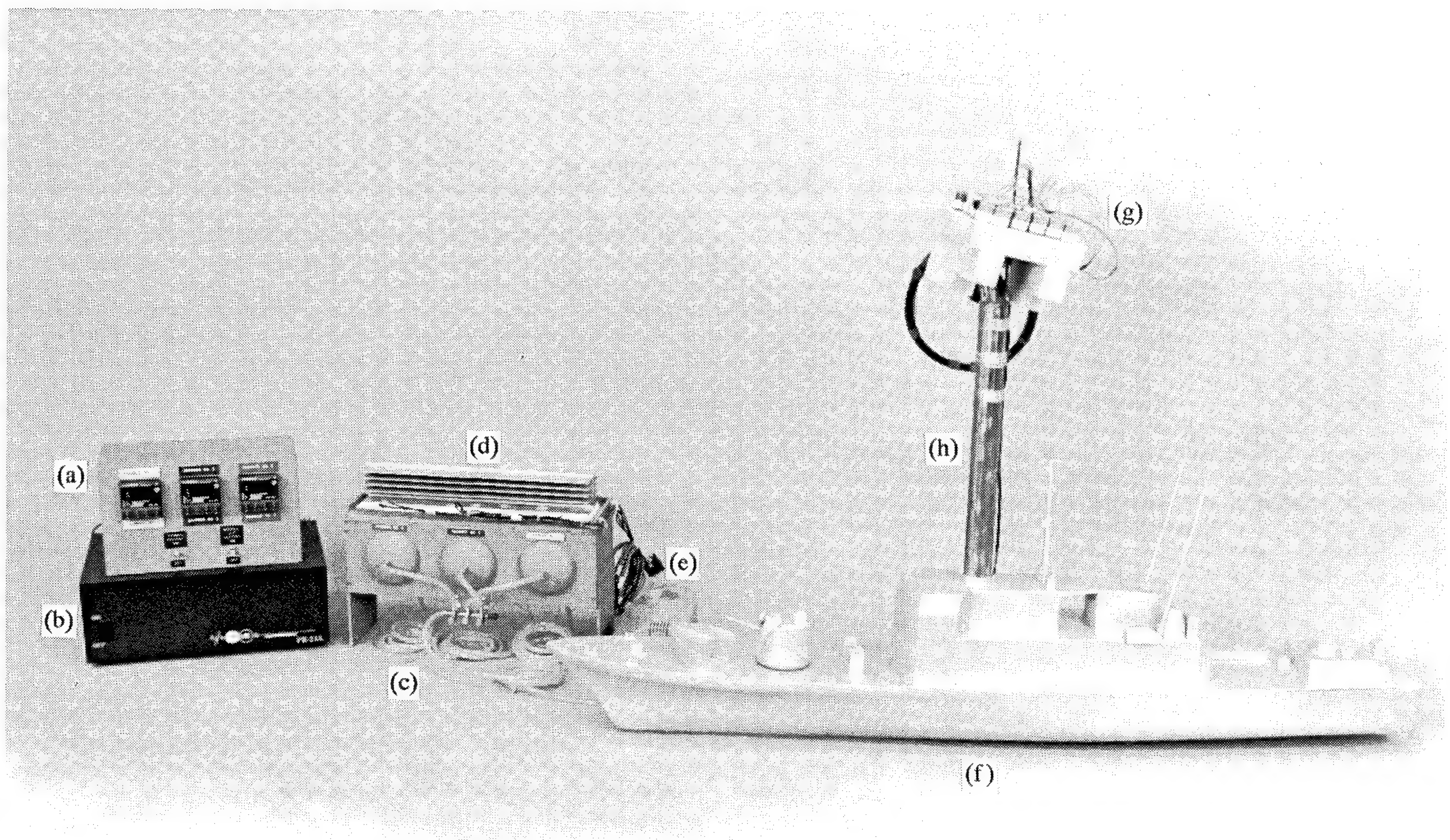

Fig. 3. Laboratory scale model and associated equipment.

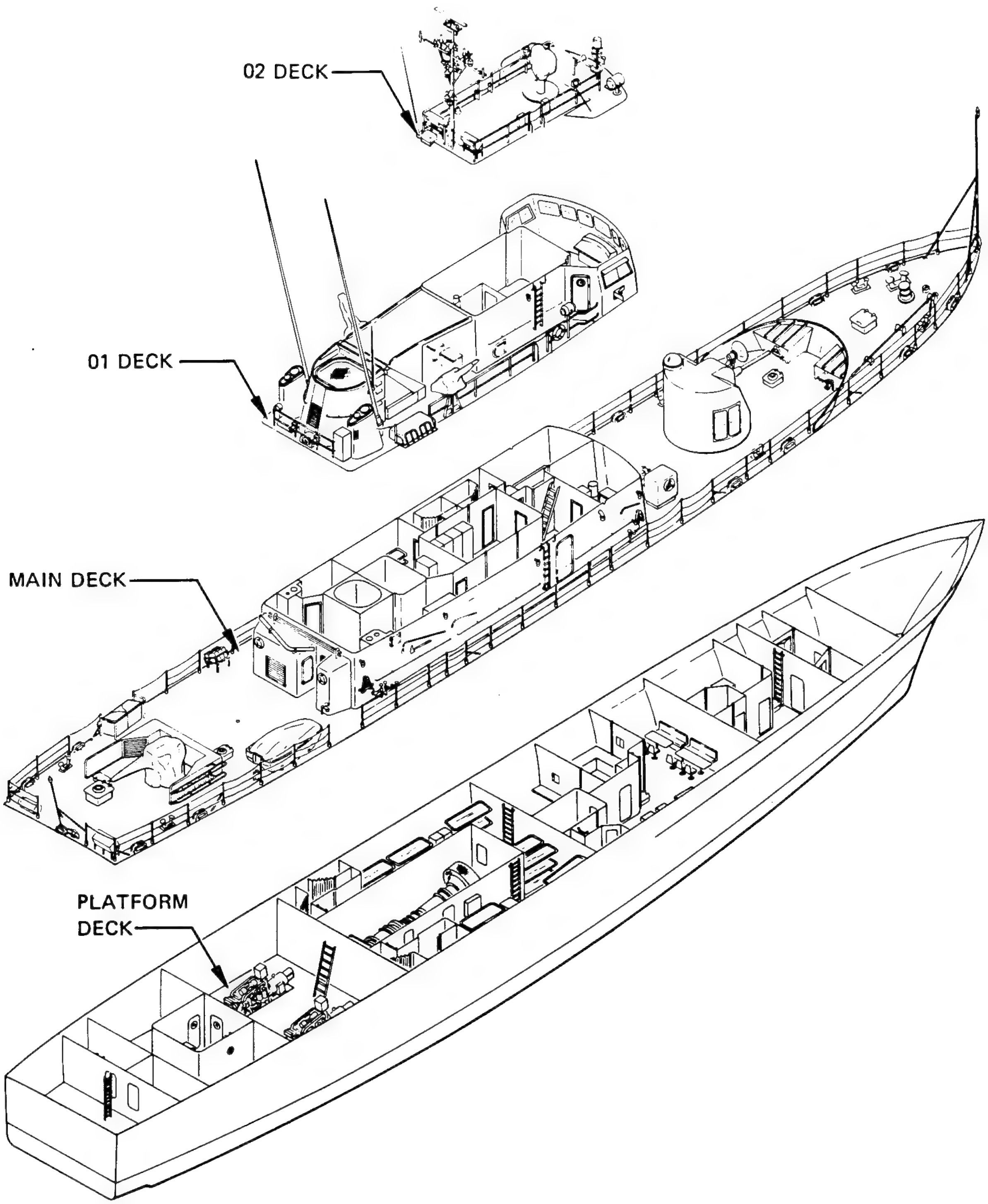

Fig. 4. Details of full-scale PG-100 patrol gunboat.

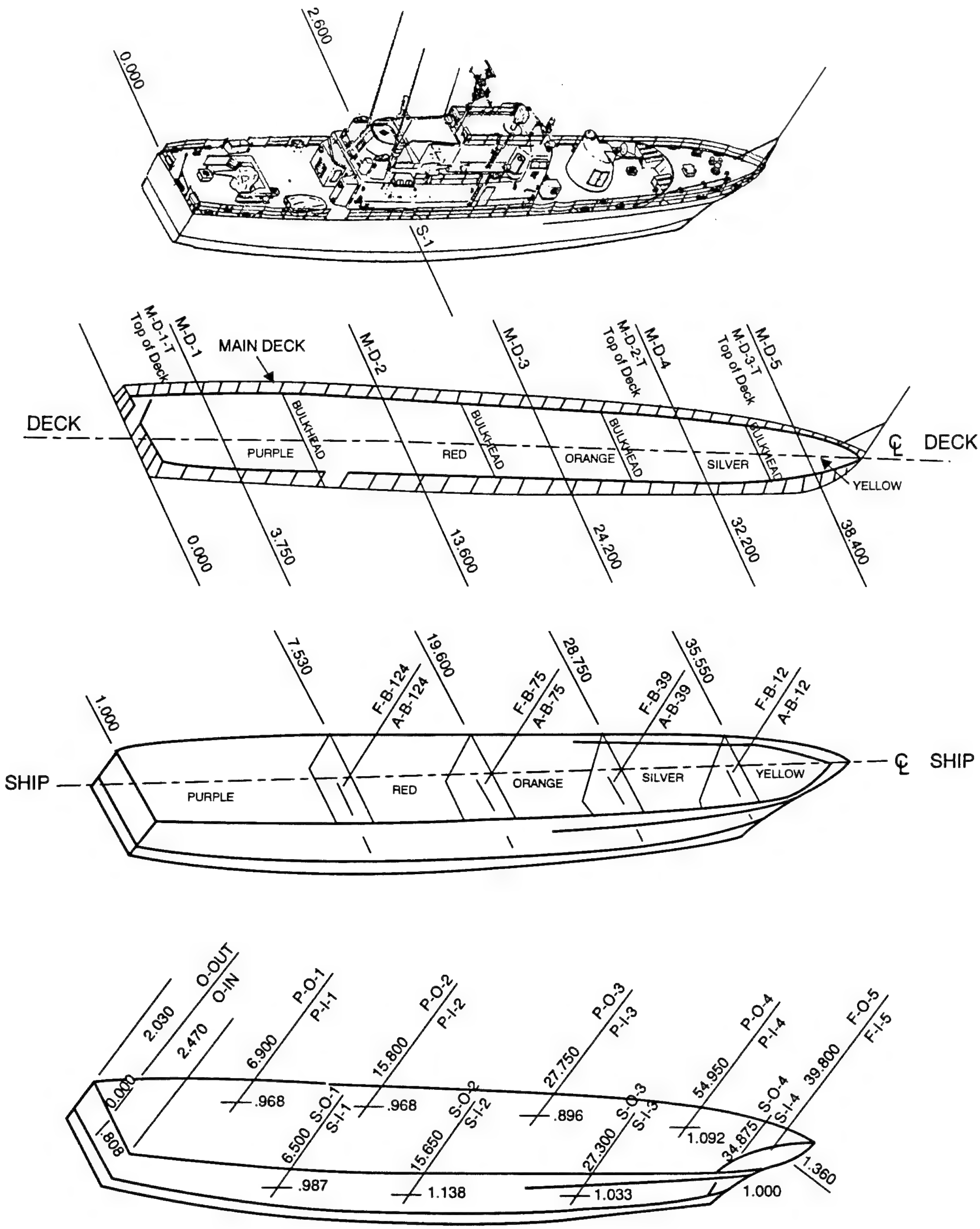

Fig. 5. Positioning of thermocouples.

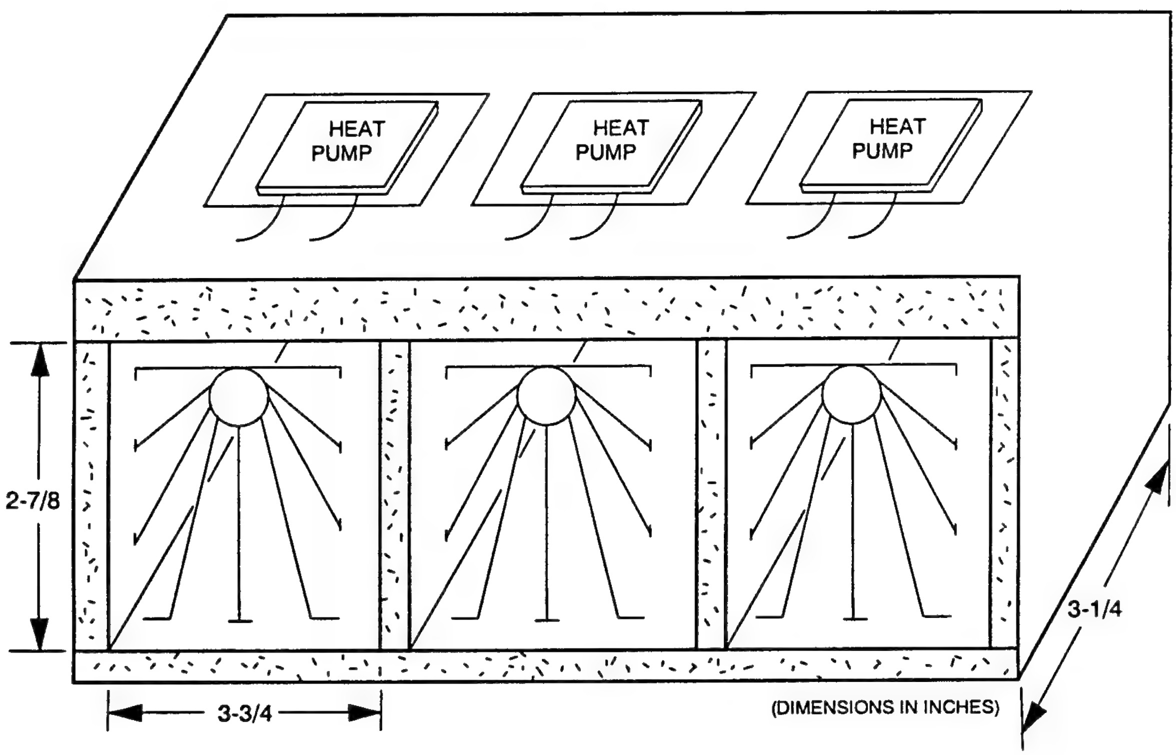

Fig. 6 Three-chamber cooler.

Water is forced to flow past the hull of the scale model, and air is forced to flow within its internal compartments. Electrical power supplied to internal resistors simulates the heat generated in the full-scale engine-room, and laboratory light sources simulate the solar heat load. When the simulation is adjusted so that the π variables of scale model and full-scale ship are the same, the result is a match between all analogous temperature functions. Qualitative features of the IR radiation expected from the scale model are the same as on a typical full-scale ship at sea such as the one shown in Fig. 7. In this LWIR image, cooler regions appear darker, while warmer regions look lighter. There is also an uneven distribution of temperature across the hull. "Hot spots" may be seen near the engine-room and the stack. A laboratory FLIR that has been aimed at a scale model under realistic simulation conditions should replicate Fig. 7 in the LWIR band.

EXPERIMENT AND MEASUREMENTS

The goal of the IR scale model experiment considered is to establish the functional form of the dimensionless temperature

$$\bar{T} = \bar{T}(\bar{x}, \bar{t}, \bar{H}, \bar{h}), \tag{2}$$

which may be considered the source of the IR radiation. Thus it is required to measure $\bar{T}$ and the dimensionless variables upon which it depends, i.e, $\bar{x}$, $\bar{t}$, $\bar{H}$, and $\bar{h}$. The dimensionless variables are not being measured directly, but as a function of the regular variables from which they are defined. These definitions are given in Table 1. Of course, the dimensionless variables also depend upon physical parameters characteristic of the scale model and its environment. Table 2 lists the regular variables that are to be directly measured using the instruments in Table 3. The required physical parameters are provided in Table 4. The various variables, parameters, and measuring instruments and their relationship to the dimensionless variables are summarized in Table 5.

A typical IR scale model experiment requires that numerical values be assigned to the parameters in Table 4 and to the variables in Table 2. The parameters are fixed throughout the course of an experiment, or indeed for a whole series of experiments. The parameters pertaining to the material of the scale model (e.g., L, k, α, and ϵ) are typically available from the designer and/or scale model manufacturer. Parameters of air and water (e.g., k_f, ρ_f, μ, and Pr) have been tabulated and are available in thermodynamic reference tables. The arbitrary reference parameter T_∞ chosen by the experimenter may be conveniently taken to be the same as T_a. In contrast to the fixed parameters, the variables take on a range of values as the experiment proceeds and are obtained from measurements with the appropriate instruments. Thus the temperature is measured using a FLIR, thermocouples, and contact thermometers. Position coordinates are conveniently considered as external (referring to a laboratory frame of reference) and internal (referring to a scale model frame of reference). The position and orientation of the scale model must be measured in the external coordinate system. Internal coordinates may be obtained from scale model drawings supplied by the manufacturer or by micrometer measurements using precise positioning. The time variable is measured by a laboratory stopwatch/chronometer. The principal heat loads on any surface of the scale model arise internally from energizing the electrical resistance and externally from

Fig. 7. Example of full-scale IR imagery.
(Courtesy of R. Schwartz, NSWCCD)

Table 1. Dimensionless variables.

Dimensionless Variables	Definition
$\overline{T}$	$(T-T_{\infty})/T_0-T_{\infty})$
$\overline{x}$	x/L
$\overline{t}$	$\alpha t/L^2$
$\overline{H}$	$H\ L^2/k(T_0-T_{\infty})$
$\overline{h}$	$h\ L/k$

Table 2. Measurement variables.

Symbol	Measurement Variable	Expected Range	Standard Deviation
$T_0(x)$	Initial temperature, °F	32-120	σ_{T_o}
$T(x,t)$	Temperature, °F	32-120	σ_T
x	Position, m	0-3 1/3	σ_x
t	Time, min	0-60	σ_t
i	Electric current, amp	0-1	σ_i
I	Surface irradiance, kW/m^2	0-5	σ_I
∇T	Temperature gradient, °F/mm	0-10	$\sigma_{\nabla T}$
T_a	Air temperature, °F	32-100	σ_{T_a}
T_w	Water temperature, °F	40-60	σ_{T_w}
$\vec{v}_a$	Airflow velocity, mph	0-20	σ_{v_a}
$\vec{v}_w$	Waterflow velocity, mph	0-10	σ_{v_w}

Table 3. Instrumentation list.

Instruments	Variable
FLIR	T
Thermocouple	T
Contact Thermometer	T
Precise Positioning System/ Model Drawing	x
Stopwatch/Chronometer	t
Ammeter	i
Radiometer	I
Pitot Tube	v
Goniometer/Protractor	θ

Table 4. Thermodynamic parameters.

Symbol	Parameters	Standard Deviation
T_{∞}	Arbitrary reference temperature	$\sigma_{T_{\infty}}$
L	Typical model length	σ_L
α	Thermal diffusivity	σ_{α}
k	Thermal conductivity	σ_k
k_f	Fluid thermal conductivity	σ_{k_f}
L_f	Typical convection length	σ_{L_f}
ρ_f	Fluid density	σ_{ρ_f}
μ	Viscosity	σ_{μ}
ϵ	Surface emissivity	σ_{ϵ}
σ	Stefan's constant	σ_{σ}
Pr	Prandtl number	σ_{Pr}

Table 5. Relationship between dimensionless variables and measurements.

Dimensionless Variables	Measurement Variables	Fixed Parameters	Instruments
$\overline{T}$	T_o, T	T_∞	FLIR, thermocouple, thermometer
$\overline{x}$	x	L	Drawings, precise positioner
$\overline{t}$	t	k, L	Stopwatch/ chronometer
$\overline{H}$	i, I, T_o	L, k, T_∞	Ammeter, radiometer
$\overline{h}$	∇T, T_a, T_w, $\overline{v}_a$, $\overline{v}_w$	k, k_f, L_f, ρ_f, μ, ϵ, σ, Pr	Thermocouple, thermometer, Pitot tube, goniometer/ protractor

impinging light radiation. An ammeter is used to read off the current that provides the i^2R power to the resistor. A radiometer is placed at positions along the model surface to measure the intensity of incident radiation. The relevant fluid magnitudes of velocity, for instance of air and water, are measured using a Pitot tube. The direction of the fluid flows must also be measured.

The quality of a given IR scale model experiment can only be assessed if the proper care is exercised to assign error bars to the quantities involved. In particular, all instruments used in the measurements (Table 3) must be calibrated before use. Thus for each instrument, all known sources of systematic error will have been removed and a measure of the expected variance, σ^2, upon repeated measurements will have been assigned. Similarly the parameters (Table 4) must not only be given magnitudes, but must also be assigned variances, σ^2. In this way it is possible, using the rules of error propagation, to ensure that the measured variance in the dimensionless temperature $\overline{T}$ be within expectations based upon errors in the measurements and defining parameters.

It is useful to be able to summarize the results of a given experiment in graphical form such as the one shown in Fig. 8. $\overline{T}$ is plotted along the ordinate axis as a function of one of its independent dimensionless variables π, where π stands for any of the variables $\overline{x}$, $\overline{t}$, $\overline{H}$, and $\overline{h}$. Note that each experimental point is plotted together with a corresponding error bar.

SUMMARY AND CONCLUSIONS

The laws of similitude in the IR may be used to design a measurements plan for studies based upon scale models. The most important ideas from the theory of IR scaling have been reviewed in this report. Among these is the notion that when the appropriate set of dimensionless variables is set equal on scale model and full-scale ship this leads to equal dimensionless temperatures on both. Hence, the observation of IR radiation on full-scale ships may be replaced by such observation on scale models in a laboratory environment.

It is of interest to apply IR scaling methods to an existing scale model. Such a scale model has been described in detail, and a series of laboratory measurements has been outlined. The specific definitions of the dimensionless variables appropriate to such measurements have been defined. The variables that are to be directly measured are listed along with the instruments to be used. Also listed are the needed thermal parameters that characterize the materials of the scale model and its environment.

As emphasized, an error analysis must be implemented in order that the IR scaling experiment may be given a meaningful interpretation. All measurements must therefore be carried out with calibrated instrumentation. This eliminates known sources of systematic error from the measurements and allows the assignment of a statistical measure of their expected variance. The expected errors in the thermal material parameters must also be known. With this information in hand, an analysis may be carried out to ensure that the measured deviations fall within the estimates obtained from an error propagation calculation.

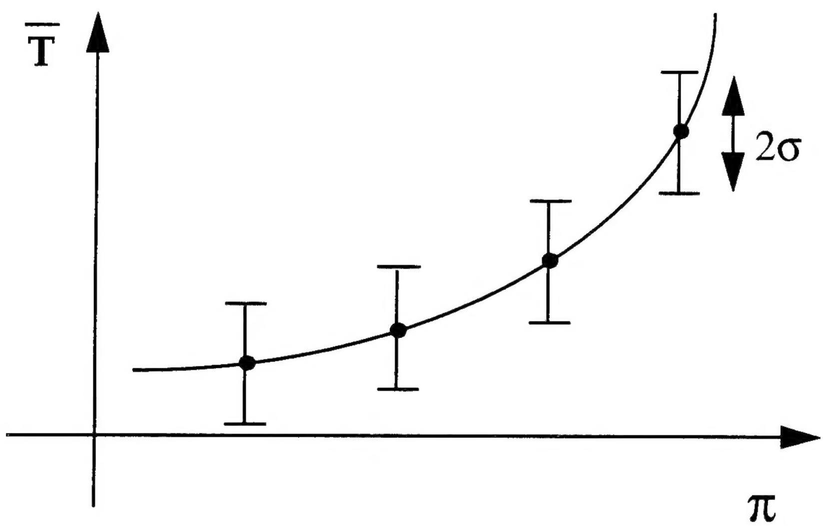

Fig. 8. Plot of dimensionless temperature, $\overline{T}$, versus π where π may be $\overline{x}$, $\overline{t}$, $\overline{H}$, and $\overline{h}$.

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